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SYNCHRONOUS PHASE AVERAGING METHOD FOR MACHINERY DIAGNOSTICS

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Abstract: This paper discusses a new diagnostic signature analysis algorithm called Synchronous Phase Averaging (SPA) which performs signal enhancement on quasi-periodic waveforms common in machinery and/or gearbox diagnosis. Time domain averaging (TDA) is an effective technique for extracting periodic signals from noisy or complex waveforms associated with machinery vibration. Due to the quasi-periodic nature of machinery shaft rotational speed, TDA is usually initiated with a trigger-pulse synchronous signal in order to synchronize the averaging process with the shaft rotation. This process is called Synchronous Time Averaging (STA), and is a common diagnostic tool in mechanical signal analysis. The Synchronous Phase Averaging method discussed in this paper can provide such signal enhancement performance but does not require a tachometer, or once-per-revolution input, as the reference signal. This is achieved through a novel synchronization process called the Phase Synchronized Enhancement Method (PSEM) which transforms a quasi-periodic synchronous (Sync or RPM) component within a vibration signal into a pure-tone discrete component. Within this newl̦ transformed PSEM sigr ꞁl, since all the Sync-relꬴ꜔d components become discrete, standard Time Domain Averaging can be directly applied to the new signal to achᎥ꜔e signal enhancement. The elimination of tachometer monitoring reduces both instrumentation and data acquisition requirements, but most importantly, allows the effective implementation of non-intrusive sensors (accelerometer, acoustic) in applications such as gear box diagnostics, etc. Application examples using the SPA method for gearbox diagnostics will be demonstrated in this paper.

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NOMENCLATURE

PSD   Power Spectral Density Function
PSEM   Phase Synchronized Enhancement Method
STA   Synchronous Time Average
SPA   Synchronous Phase Average
N   Synchronous (Rotating) Frequency
Sync   Synchronous Frequency Component or RPM Frequency
FM   Frequency Modulation
IF   Instantaneous Frequency

INTRODUCTION: Time domain averaging (TDA) is a well-known and powerful technique for extracting periodic signals from noisy or complex waveform. For this process to be coherent, it requires that the period of the signal to be extracted be known or assumed. I is based on averaging points one period apart, where the period is that of the signal to be extracted. However, in machinery diagnosis, the quasi-periodic nature of shaft rotational speed does not allow direct application of TDA. Therefore, TDA is usually performed by utilizing a trigger-pulse synchronous signal, such as a once per revolution tachometer signal, in order to synchronize the averaging process with shaft rotational motion. Such Synchronous Time Averaging is generally considered a key method for analyzing gear behavior [1, 2, 3]. Though an important point to be made is that when performing synchronous time averaging only the first sample of each period of the ensemble signal is synchronized to the rotating shaft.

In theory, the most perfect form of time averaging utilizes external sampling where the sampling process speeds up or slows down with the shaft rotational speed [4]. When engine rotational speed(s) varies, the sampling does also yielding non-uniform sample intervals in acquired data. However, the rotational phase angle between consecutive samples maintains absolutely constant. When time avei aging is applied, the complete cycle of data points within each ensemble is synchronized to the rotating shaft rather than just the first sample of the collection as is the case with synchronous time averaging. Such an ideal averaging process provides superior diagnostic signal enhancement capability. Unfortunately, the luxury of an optical encoder is usually not available. In addition, the requirement to have a speed measurement as the reference signal for STA is somewhat impractical within some operational environment where intrusive instrumentation is not possible, such as gear box diagnostics using remote acoustic measurements. Therefore, it is highly desirable to develop a waveform enhancement technique which does not require tachometer or key-phaser input as the STA would require.

This paper discusses a new algorithm called Synchronous Phase Averaging (SPA) which provides the same degree of signal enhancement as external sampling without sophisticated and intrusive external sampling instrumentation and data acquisition systems. Moreover, SPA does not even require a tachometer based reference signal for triggering data acquisition. This is achieved through a novel signal transformation technique called the Phase Synchronized Enhancement Method (PSEM) [5]. The PSEM

utilizes the instantaneous phase information associated with the quasi-periodic shaft rotational motion to transform the synchronous (Sync or RPM) component into a pure-tone discrete component. This Sync discretization process generates a highly desirable effect on the entire diagnostic signal where all other Sync-related components automatically become discrete. Within this newly transformed PSEM signal, all spectral components which are nonlinear correlated with Sync, such as Sync harmonics, are automatically discretized. In a rotor system, different rotational mechanisms could interact with one another due to some nonlinear process [6, 7, 8, 9]. Such nonlinear correlation plays a significant role in accurate mechanical signature diagnosis, and can be identified from its dynamic response signal using nonlinear spectral analysis techniques such as bi-coherence, tri-coherence, and hyper-coherence, etc. [10, 11, 12]. Once all the sync-related components within the PSEM signal become discrete, standard Time Domain Averaging can be directly applied to the PSEM signal to achieve signal enhancement. Thus, Synchronous Phase Averaging provides the same signal enhancement performance which external sampling achieves without the related expense and tachometer requirement.

PHASE SYNCHRONIZED ENHANCEMENT METHOD (PSEM): A vibration signal in a rotor system can be modeled as an FM signal with multiple spectral components at different center (carrier) frequencies. The instantaneous frequency (IF) and/or Instantaneous Phase (IP) information of each component can be recovered using several digital frequency demodulation methods, such as the complex demodulation (heterodyne) techniques. [13] and Phase Lock Loop (PLL) [14] method. During steady state operation of most machinery systems, the instantaneous frequency of Sync tends to fluctuate about some center frequency and is not a constant frequency. Since the amplitude of such frequency variation could be much smaller than the bandwidth within PSD analysis, the Sync spectral component still appears as a very discrete peak in its PSD. Based on this phenomenon, the PSEM Method was developed to take advantage of such IF variation phenomenon. The basic principle of the PSEM is to force the narrow-band spectral component of Sync whose frequency is fluctuating slightly around some center frequency into a pure-tone discrete component of constant frequency. This discretization process thus generates a highly desirable effect on the entire signal, i.e., all other spectral components which are correlated with Sync (such as Sync Harmonics, Gearmesg, etc.,) automatically become discrete.

The signal model can be formulated as:

$$x(t') = A\cos[\Psi(t')] + B\cos[\gamma * \Psi(t')] \qquad (1)$$

$$\qquad\qquad \Uparrow \qquad\qquad\qquad \Uparrow$$

$$\qquad\qquad \text{SYNC} \qquad\quad \text{SYNC-RELATED}$$

Where $\Psi(t)$ is the instantaneous phase of sync

γ is a constant

The first term A*cos[Ψ(t')] represents the Sync frequency component, while the second term B*cos[$\gamma*\Psi$(t')] represents a Sync-related component whose phase variation is synchronized with Sync. The sampling process of the original signal can be viewed as an observer traveling at a constant speed V(t) along the time-axis observing the waveform x(t'). If the observer is traveling at a time-dependent non-constant speed V(t), he will then observe a slightly different waveform y(t) as:

$$y(t) = x[t' = V(t)t] = A\cos\{\Psi[V(t)t]\} + B\cos\{\gamma*\Psi[V(t)t]\} \qquad (2)$$

This new waveform y(t) will generate new phase information for both the sync and the sync-related components. However, the new phase of the Sync-related component is still synchronized with the phase of Sync as shown in equation (2). This relationship indicates that phase correlation between two spectral components is independent of the sampling process.

The waveform of the Sync frequency component under a constant sampling rate is typically quasi-periodic. This sync component then can be discretized by resampling with a unique time-dependent sampling rate so that the newly-generated waveform will become periodic instead of quasi-periodic. This unique time-dependent sampling rate can be found from the instantaneous phase information of Sync. The signal model of Sync can be rewritten as:

$$x(t) = A(t)\cos[\omega_c t + \Phi(t)] \qquad (3)$$

Where: ω_c is the center frequency of Sync
$\Phi(t)$ is instantaneous phase variation

Since time and phase are directly related to each other, the resampling rate can obtained through the following relationship:

$$\Phi(t) = \omega_c \Delta(t) \qquad (4)$$

By replacing the instantaneous phase variation $\Phi(t)$ with $\omega_c \Delta(t)$, equation (3) becomes:

$$x(t) = A(t)\cos[\omega_c t + \omega_c \Delta(t)]$$

$$= A(t)\cos\{\omega_c[t + \Delta(t)]\} \qquad (5)$$

Equation (5) states that, by treating the original quasi-periodic signal as a resampled signal represented by equation (5), the resampled signal will become periodic since the original phase variation is now transformed into its corresponding time variation $\Delta(t)$.

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Once the Sync frequency component becomes discrete in the resampled signal, all the other Sync-related components will automatically become discrete.

Figure 1 shows the PSEM algorithm. The input signal is composed of a reference Sync component along with several other Sync-related and non-Sync-related components. The band-pass filter first removes all the other spectral components in order to generated the time history of a quasi-periodic Sync component. The instantaneous phase variation signal $\Phi(t)$ of Sync is then estimated with the Hilbert Transform method. With the relationship between phase and time, this phase variation signal can now be converted into a realignment time signal $\Delta(t)$. The uniform sampling interval of the original signal is then remapped onto an array of non-uniform sampling intervals based on the realignment time. This realignment process will transform the original quasi-periodic signal into a periodic signal. An interpolator is then used to recover the uniformly sampled periodic signal from the non-uniformly sampled signal. Notice that, once the realignment time signal $\Delta(t)$ is identified, the remaining realignment process will be performed on the original signal rather than the band-pass filtered signal. As a result, all the other Sync-related components in the signal will automatically become discrete.

With its unique capability of transforming a quasi-periodic Sync into a pure-tone discrete component, PSEM generates a highly desirable effect on an entire diagnostic signal with all Sync-related components becoming discrete. With this enhanced frequency resolution, the PSEM signal can recover detailed spectral information useful in diagnostic evaluation. This method is especially useful for machinery diagnostics; in which case a quasi-periodic driving process (Sync) generates many other rotational components. These related components such as Sync harmonics, bearing element spin and passing frequencies, modulation and sideband components can provide useful information about a machine's operational condition.

In this section, test data from an application example is used to demonstrate this PSEM technique. The PSD shown in figure 3-a is taken from a spi_dle motor during a vibration test. The FFT block size is 16K, which gives a very high bandwidth resolution of 1.6 Hz. In this PSD, the sync frequency component N, and its harmonics such as 2N, 3N, 8N and 9N are readily observable. In addition, many other Sync-related components such as the cage frequency component C, the Inner ball pass component I, the ball spin frequency component B, and many other related components such as their harmonics and modulations are evident. During steady state operation, the fundamental Sync frequency is very constant. Therefore, a PSD of spindle motor vibration data shows a very discrete peak at synchronous frequency. A joint time-frequency plot (isoplot) of the test data also shows a very stationary peak at sync whose frequency never moves outside an analysis frequency bin (unit bandwidth).

However, instantaneous frequency analysis indicates that the fundamental Sync frequency component is by no means a perfect discrete. Figure 2 show the instantaneous frequency of Sync, Inner Ball Pass (IBP) and the 8-th harmonic of Sync. The IF of these components are all moving periodically. In addition, the frequency variation of Sync is
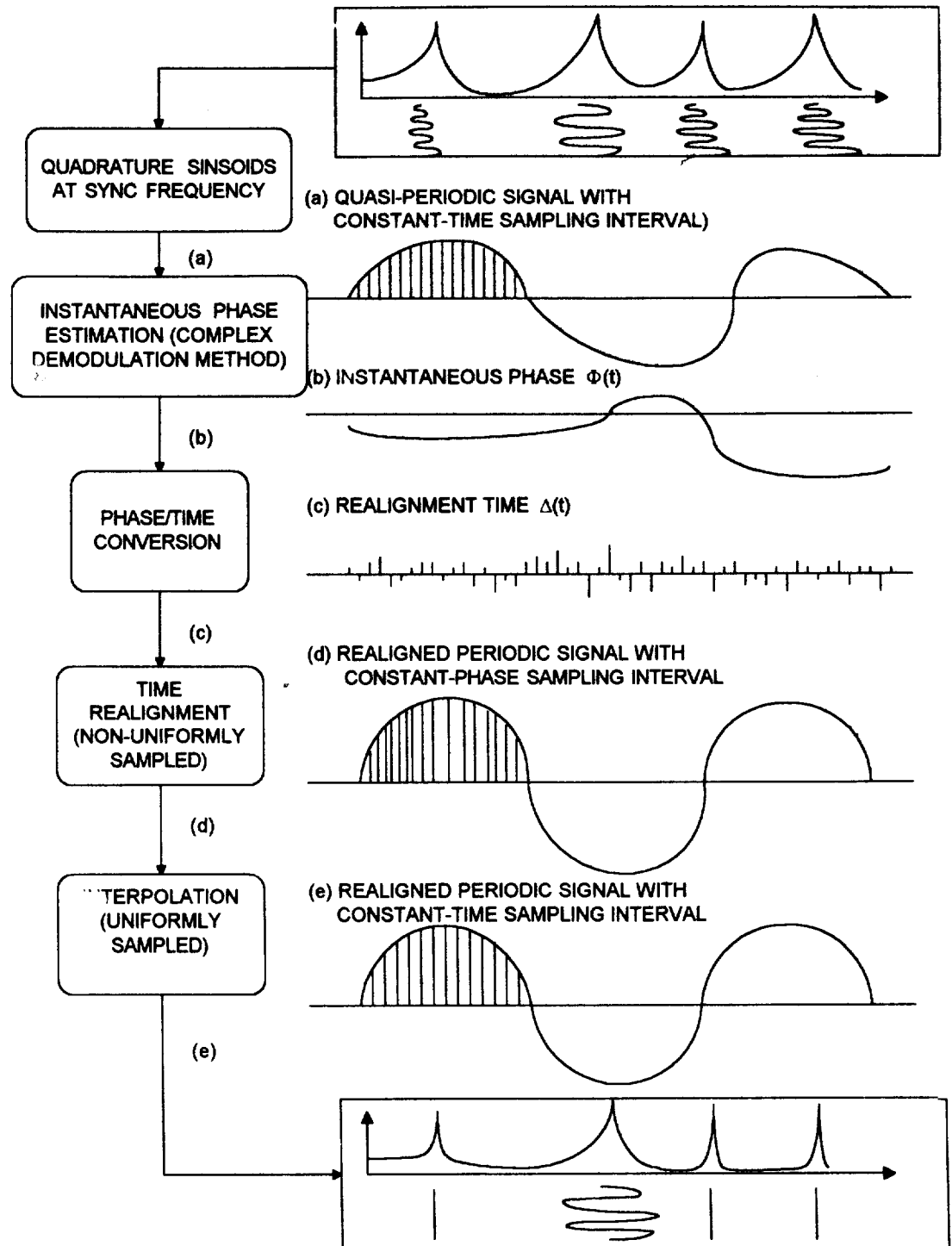
FIGURE 1 PHASE SYNCHRONIZED ENHANCEMENT (PSEM) ALGORITHM
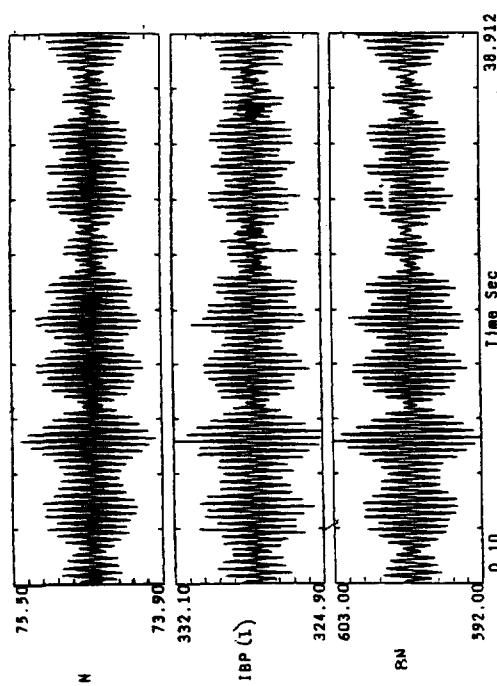
The flowchart boxes read:

QUADRATURE SINSOIDS AT SYNC FREQUENCY

INSTANTANEOUS PHASE ESTIMATION (COMPLEX DEMODULATION METHOD)

PHASE/TIME CONVERSION

TIME REALIGNMENT (NON-UNIFORMLY SAMPLED)

INTERPOLATION (UNIFORMLY SAMPLED)

(a) QUASI-PERIODIC SIGNAL WITH CONSTANT-TIME SAMPLING INTERVAL)

(b) INSTANTANEOUS PHASE $\Phi(t)$

(c) REALIGNMENT TIME $\Delta(t)$

(d) REALIGNED PERIODIC SIGNAL WITH CONSTANT-PHASE SAMPLING INTERVAL

(e) REALIGNED PERIODIC SIGNAL WITH CONSTANT-TIME SAMPLING INTERVAL

Figure 2: Instantaneous frequencies of (a) Sync, (b) Inner Ball Pass, (c) 8N, of Spindle Motor Data.
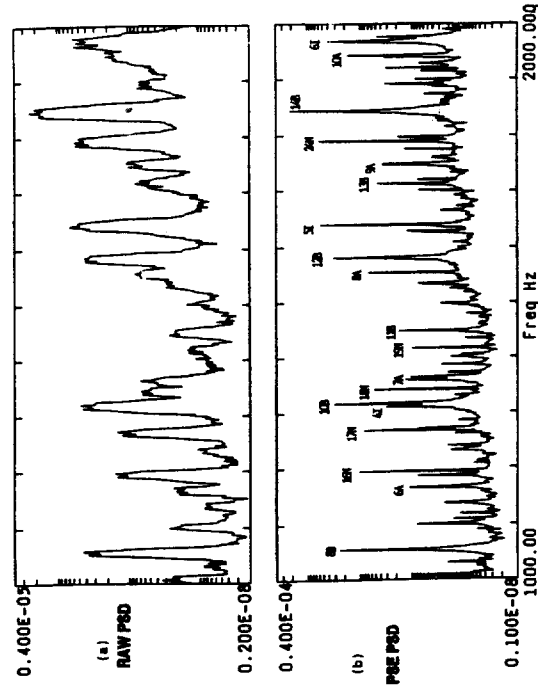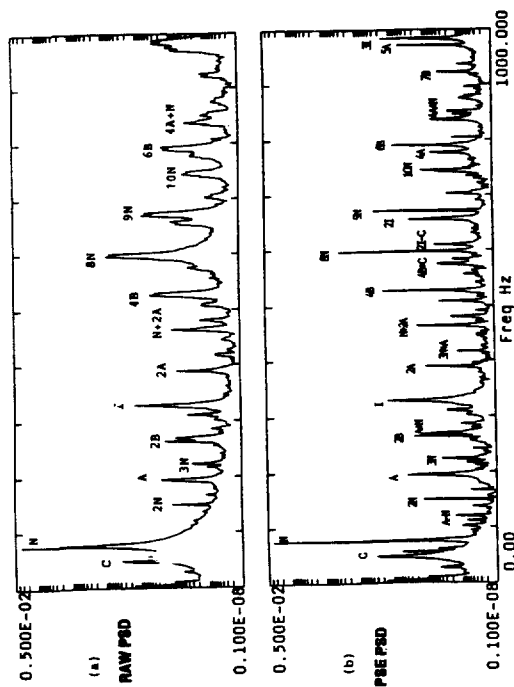
Figure 3: PSDs of (a) Raw Signal (b) PSEM Signal from 0 to 1000 Hz of Spindle Motor Data

Figure 4: PSDs of (a) Raw Signal (b) PSEM Signal from 1000 to 2000 Hz of Spindle Motor Data
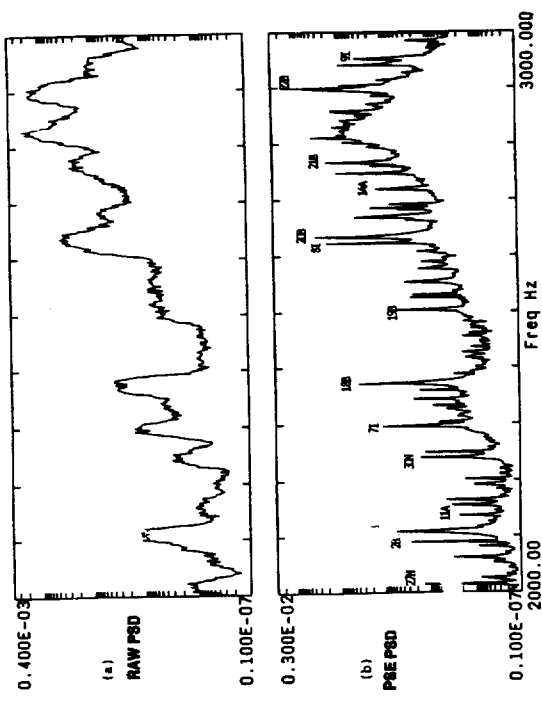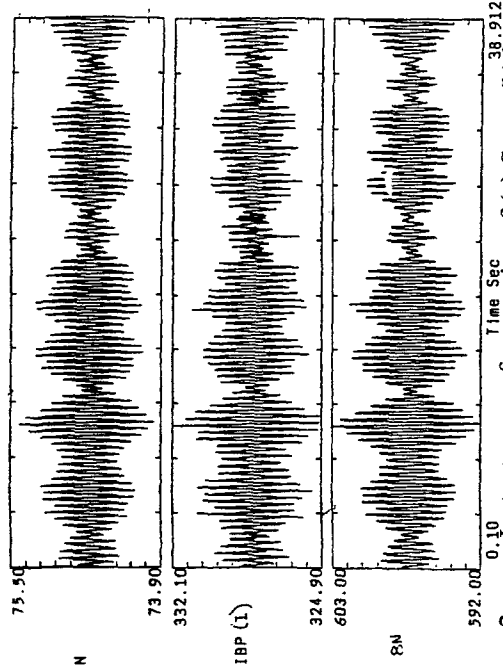
Figure 5: PSDs of (a) Raw Signal (b) PSEM Signal from 2000 to 3000 Hz of Spindle Motor Data

Figure 2: Instantaneous frequencies of (a) Sync, (b) Inner Ball Pass, (c) 8N, of Spindle Motor Data.
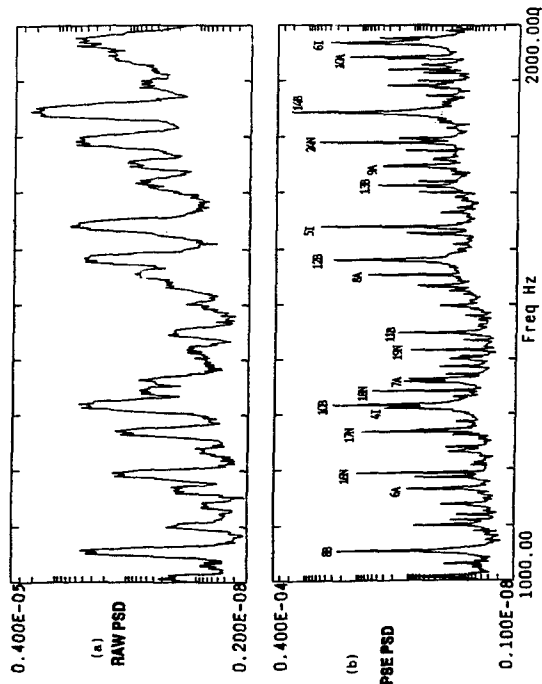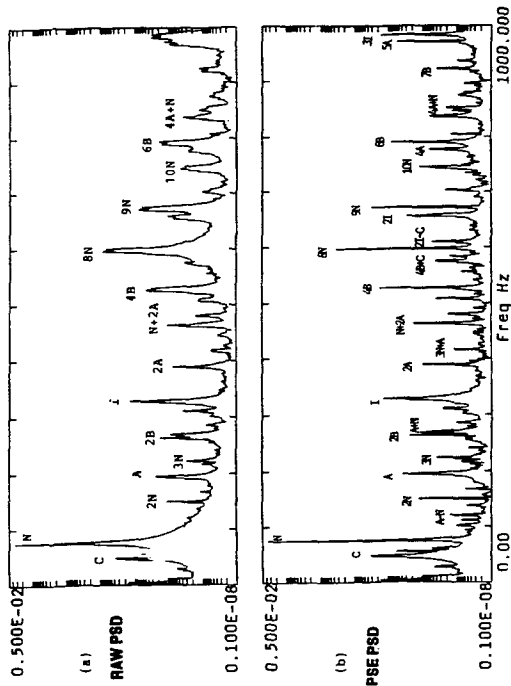
Figure 3: PSDs of (a) Raw Signal (b) PSEM Signal from 0 to 1000 Hz of Spindle Motor Data

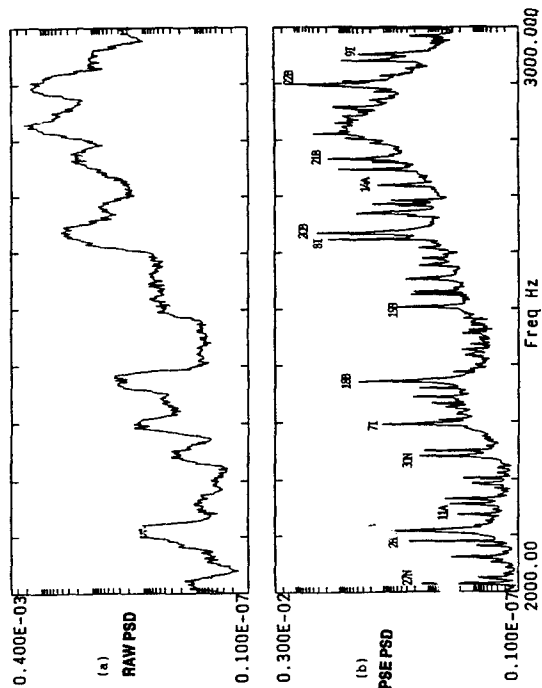Figure 4: PSDs of (a) Raw Signal (b) PSEM Signal from 1000 to 2000 Hz of Spindle Motor Data

Figure 5: PSDs of (a) Raw Signal (b) PSEM Signal from 2000 to 3000 Hz of Spindle Motor Data

within 1.5 Hz, which is less than the bandwidth of the PSD. Based on this IF information, the PSEM algorithm forces the frequency of Sync from this periodic variation into a constant frequency. As a result, a highly desirable effect is generated on the entire signal.

Figure 3-a and 3-b show the ordinary RAW PSD and the enhanced PSEM PSD of the test data. The frequency range is from 0 to 1000 Hz. Since all the Sync-related components become discrete, the signal's frequency resolution becomes much sharper. The original raw PSD shows a broad peak near 1000 Hz, but the enhanced PSD resolves it into two spectral peaks with the first one being the 5-th harmonic of the Outer Ball Pass (OBP) component while the second one is the third harmonic of the IBP component.

The signal enhancement effect becomes much more noticeable in the higher frequency region. Figures 4-a and 4-b are the raw and enhanced PSEM PSDs of the same data set from 1000 to 2000 Hz. In the raw PSD, all the peaks become so broad that all the spectral information is smeared. However, the enhanced PSD recovers all the sync-related components such as 8 times, 10 time, 12 times and 14 times of Ball Spin (BS) components, 6, 7, 8, 9, and 10 times of OBP frequency, and the harmonics of Sync at 16N, 17N, 18N, up to 24N.

At higher frequencies, PSEM signal enhancement capabilities become even more evident. Figure 5 shows respectively the Raw and enhanced PSEM PSDs from 2000 to 3000 Hz. Again, the enhanced PSEM PSD recovers all the spindle motor Sync-related components such as 16, 18, 20 and 22 times of BS frequency component. These components are completely hidden in the original spindle motor mechanical signature analysis PSD.

SYNCHRONOUS PHASE AVERAGING (SPA) METHOD: As discussed in the last section, the PSEM can transform a quasi-periodic sync into a pure-tone discrete component. Within this newly transformed PSEM signal, since the sync and sync harmonics become discrete, standard Time Domain Averaging can be directly applied to the PSEM signal to achieve signal enhancement. Thus, Synchronous Phase Averaging can provide signal enhancement performance without the related expense and tachometer requirement. The elimination of tachometer monitoring reduces instrumentation, data acquisition, and most importantly would allow direct application to remote sensing such as gear box diagnostics using a single acoustic or accelerometer measurement.

Successful application examples are utilized to demonstrate the performance of the SPA techniques for gearbox diagnostics. The test data were captured from externally mounted accelerometers of a gearbox with both input pinion and output gears having 27 teeth. The shaft rotational frequency is running at approximately 71.7 Hz during the tests, therefore, the predicted gear mesh frequency is approximately 1935 Hz (27N). Six sets of test data from the gearbox are used to demonstrate this SPA application.
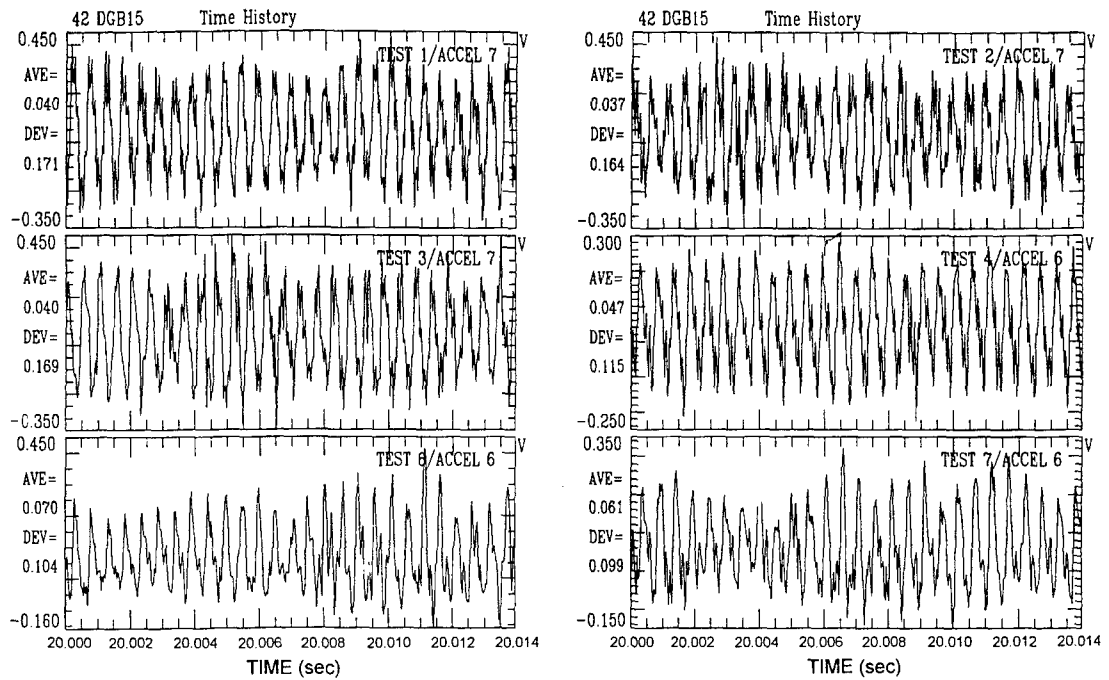
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Figure 6   RAW Signal of 42 Degree Gearbox Data with 500 Averages (Fundamental Frequency=Sync)
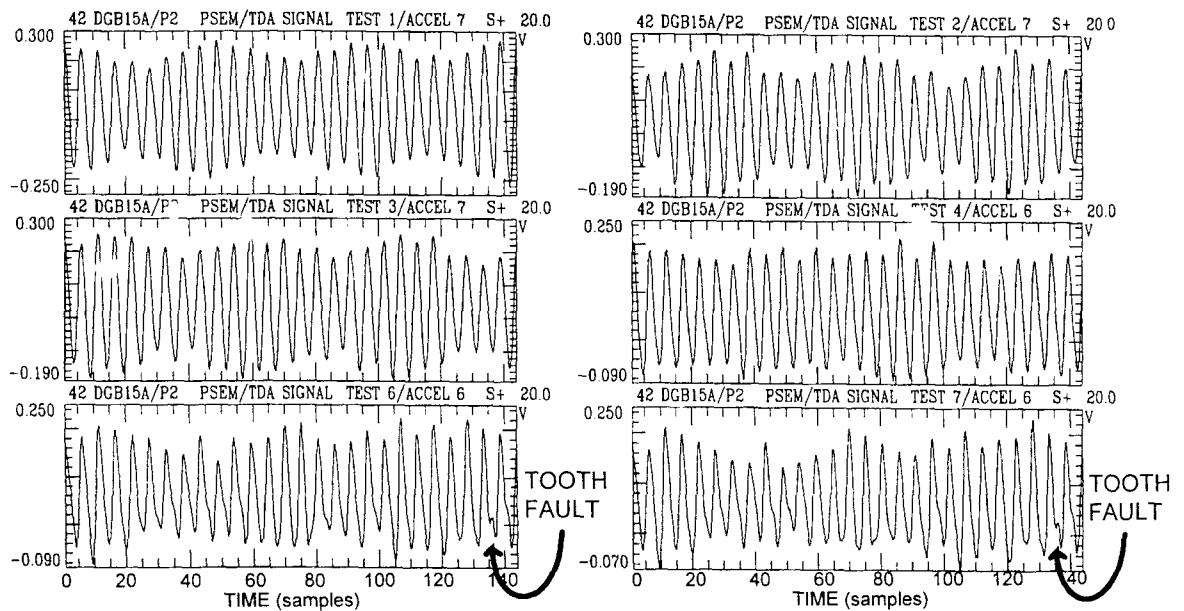

Figure 7   SPA Signal of 42 Degree Gearbox Data with 500 Averages. (Fundamental Frequency=Sync)

Figure 6 shows the raw time history of an accelerometer measurement for these 6 sets of gearbox data during one revolution of shaft rotation. The waveforms of these raw signals are all corrupted by background noise. Now, in order to perform SPA, the raw accelerometer data is first synchronized to the gearmesh frequency using the PSEM method. Since the PSEM data has now been synchronized to Sync, Time Domain Averaging is then directly applicable to the PSEM data using a TDA fundamental frequency of 71.7 Hz (Sync). Figure 7 shows the six resulting enhanced SPA signals over a full cycle of shaft rotation. The number of ensemble averages performed in the analysis is 500. Within this full cycle of shaft revolution, an enhanced signal with 27 cycles of oscillation is observed which corresponds to the tooth mesh waveform. In examining the smoothness of this waveform, a noticeable discontinuity or irregularity is readily observed in tests 6 and 7 at the 26th oscillation cycle. This discontinuity repeatedly shows up in the SPA enhanced signal at other time periods within the test. This indicates a gear tooth fault at the 26th gear tooth within the hardware used in tests 6 and 7. This results of SPA analysis correctly identify the conditions of the test gearbox of tests 6 and 7.

CONCLUSIONS: By converting the instantaneous phase signal into an equivalent resampled time signal, the PSEM technique transforms a quasi-periodic spectral component of Sync into a pure-tone discrete component. This discretization process generates a highly desirable effect on the remaining signal with all the other Sync-related components automatically becoming discrete. With this enhanced frequency resolution, the PSEM signal can recover detailed spectral information useful in diagnostic evaluation. Within this newly transformed PSEM signal, since the sync and sync harmonics become discrete, standard Time Domain Averaging can be directly applied to the PSEM signal to achieve additional signal enhancement. The SPA analysis discussed above does not require tachometer or key-phaser input as the STA would require. Such synchronization can be directly performed on any gearmesh (GM) frequency of a chosen rotor within a measured vibration signal. Since the amplitude of the GM component measured by a vibration sensor is typically strong, synchronization to various RPM within a single measurement can be achieved by tuning the PSEM reference frequency to the desired GM frequency. Therefore, the complexity of instrumentation and data acquisition requirement is reduced. Furthermore, non-intrusive sensing with applications such as gear box diagnostics using a single acoustic or accelerometer measurement becomes feasible.

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